Biomass and Sapwood of Green Ash (*Fraxinus pennsylvanica*) in the Twin Cities Metro Area

By

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ABSTRACT

A primary objective of this study was to compare field measurements to quantities predicted by established models, or model validation. A secondary objective was to examine the sapwood content, with an end to more accurate application of chemical dosages in treatments for emerald ash borer (EAB, *Agrilus planipennis*). A stem dimensional analysis, described by Woodell and Whitaker (1968), was conducted for 40 trees across a range of size classes, grown in the Twin Cities Metro Area of Minnesota. Characteristics of biomass and sapwood volume are presented. The biomass model developed by Hahn (1984) demonstrated a good fit with field data, and can be modified to accurately predict biomass content of an urban-grown green ash trees in the Twin Cities Metro Area. The model developed by Jenkins et al. (2003) was less precise compared to that of Hahn, when analyzing the field data. Sapwood was shown to have strong correlations with crown surface area and a combined height x diameter variable. A model is presented here which predicts aboveground sapwood volume with a residual standard error 8.457 cubic feet. As trees play an increasing role in the sustainable design of urban areas, it would be advantageous to know as much about their characteristics as possible. Urban woody biomass is increasingly employed as an energy source, therefore biomass estimators are needed to accurately describe this resource. With this study, measurements were used to successfully modify published models for use in urban settings.

I. INTRODUCTION

With the arrival of emerald ash borer in Minnesota, large quantities of ash wood are expected to be produced. Most municipalities have been preemptively removing trees, so as to avoid having to respond all at once to a mass mortality event, such as occurred in Ohio, Michigan and other states. A multi-agency collaboration has invested in minimizing the impact on Minnesota forests, both urban and rural. The Minnesota Department of Natural Resources estimates 0.7 million cords of urban ash wood are vulnerable to the insect, compared with 18.1 million cords of rural ash wood (Vanderschaaf and Jacobson, 2011).

The Twin Cities Metro Area is unique in its use of urban wood for energy production at the District Energy Heating & Cooling Plant. Models have not been produced to monitor or predict the mass of woody material that is being produced or will be produced in the future. Although tree woody biomass and volume models have been created for timberlands, it is unknown whether these models could be used in urban settings with low error.

Trees grow differently in urban areas than they do in the wild. Differences are due to irrigation, fertilizer, competition with turf grass, road salt, compacted soils, concrete, mechanical damage, pruning, waste from household pets and wide growing spaces that are not commonly found in a natural forest.

Chemical treatments of ash to protect against mortality from emerald ash borer are a management option. Therefore, information on sapwood volume would be useful in determining dosages. Since these chemicals do not enter the heartwood portion of a tree, but remain in the xylem or sapwood, a method for estimating the amount of xylem could allow for a more precise application of a chemical.

Although various methods have been used to estimate the biomass of urban trees, few have used destructive sampling and none have focused on one species. Two biomass models are available for the region, one published in 1984 by Jerold T. Hahn, and the other by Jenkins et al. in 2003. These models were developed for use in forest land, and it is not known how well they would apply to trees found in urban areas.

Research quantifying individual biomass of tree species has focused on natural forest stands, while few studies have been conducted on urban trees. Of the urban tree biomass studies, only one (Nowak, 1994) used destructive removal of the tree as a sample method. Other urban studies used ocular estimates (Pillsbury et al., 1998) or existing formulas developed for forest-grown trees. Most available biomass estimators rely on the correlation between the biomass content of a tree and Diameter at Breast Height (DBH). The US Forest Service Forest Inventory and Analysis (FIA) program maintains permanent research plots throughout the country, along with estimators which are used to quantify the biomass resource. FIA employs the Component Ratio Method (CRM) which uses factors such as DBH, specific wood density for a species, and known geometric relationships between tree structure and wood content. Van Deusen (2011) stated that "hardwoods tend to have less precise volume and biomass equations due to their decurrent form, which is not conformable to simple taper models or merchantable volume equations."

Nowak's study sampled 30 street trees in Chicago, using 9 different species across a range of diameters. He found that biomass was "significantly lower than predicted from allometric equations from natural forest stands." Studies using destructive sampling are uncommon, due to its cost and logistical challenges, and the high confidence in the minds of researchers in existing biomass estimators.

There are no published models to predict sapwood for green ash. Sapwood research has been published for several forest-grown species in the Western U.S, where relationships between sapwood volume and crown dimension or amount of foliage was found (Maguire and Hahn, 1986 and 1989, Maguire and Batista, 1996). Sellin (1993) found that in spruce, the heartwood ratio was significantly greater in suppressed (i.e. high competition) trees, compared to dominant trees of the same age. With this line of thinking, it is possible sapwood of open-grown widely spaced urban trees would contain higher ratios of sapwood volume than their forest-grown counterparts.

II. OBJECTIVES

The primary objective of this study was to compare field measurements to quantities predicted by established models, or model validation. Characteristics of biomass and sapwood volume will be presented. The primary aim was to quantify the biomass content of an open-grown green ash tree growing in the Twin Cities Metro Area. A secondary objective was to examine the sapwood content, with an end to provide for more accurate application of chemical dosages in treatments for emerald ash borer.

III. METHODS

A. Data

A.1 Study Area

Green ash is one of the most common trees found in the Twin Cities. It was widely chosen as a replacement for American elm (*Ulmus Americana*), following the high rates of mortality for that species during the 1960s-1980s Dutch Elm Disease outbreak. Ash was planted because it is inexpensive to produce in the nursery, grows well in a variety of conditions and provides many of the benefits that elm provided. It was chosen for this study due to the high number of trees being removed as a preemptive measure for mitigation of emerald ash borer. Most municipalities within the Twin Cities Metro Area have plans to reduce their ash component over a 10-year period, in cooperation with the Minnesota Department of Agriculture. With so many trees being removed, the opportunity for research was present.

Due to the increased cost of removal and weighing of biomass, it was not practical to expect one single municipality to provide all of the research trees. Therefore, trees were measured in Minneapolis, St. Paul, Minnetonka, and Eagan, over a period of two years, starting in winter of 2011, through the summer and fall of 2012, ending in winter of 2013.

A.2 Measurements

Forty trees comprised of seven size classes were selected using the following criteria:

- Open grown
- Live tree
- Single stem (i.e. not forking below breast height)
- Planted (i.e. not a wildling)
- On public property
- Size classes (actual number of trees measured in parentheses):
    - 3-5’’ – 5 trees (8)
    - 6-10’’ – 4 trees (7)
    - 11-15’’ – 4 trees (5)
    - 16-20’’ – 4 trees (4)
    - 21-23’ – 4 trees (4)
    - 24-26’’ – 4 trees (4)
    - 27-30’’and over – 5 trees (5)

Prior to removal, trees were photographed and measured for their crown width, height and diameter at breast height. Crown vertical length was later obtained from photo analysis.

Cross sectional wood samples (cookies) were taken from each tree, beginning at breast height, then at 4 foot increments ascending to the primary branch union. Wood samples were also taken from each main branch, at its union with the main stem. Branch length was also measured. All material from each tree, save the wood samples, was then weighed either in a truck (for large trees) or on a portable digital scale (for smaller trees).

Each wood sample was examined in the laboratory. Photographs and measurements for age, sapwood and heartwood diameter were taken. Wood samples representing breast height were dried in sealed kiln. These samples were weighed successively over a period of three to five days until no weight change was observed.

Since the sample trees came from several cities over the course of two years, slight differences exist in the method of weighing the material when an industrial scale was used. Different trucks, different drivers, different routes to the scale, and different scales were used. This was unavoidable due to lack of necessary funding, and the desire not to add too much work to the city work crew’s schedule. The scale closest to the tree removal job site was chosen, to minimize cost to the city.

To verify the accuracy of the industrial scale weight measurements, a summed-sections approach was used. Photo analysis software was used to estimate sections that were not measured at time of tree removal. Volumes for main stem sections were estimated using formulas for a truncated paraboloid, while branch sections were estimated using formulas for a cone, depending on the shape of the section, as ascertained from photos.

Truncated paraboloid formula = 0.0027274*(top diameter^2+bottom diameter^2)*length of section (diameter in inches, length of section in feet)

Conical formula = 0.3333 * cross-sectional area * Length of section

Two different constants were used, depending on the size of the branch section: 0.55 for larger branches, 0.3333 for smaller branches.

Larger branches volume = 0.55 * cross-sectional area * Length of section

These cubic foot volumes were summed, then multiplied by 60 pounds per cubic foot (Miles and Smith, 2009, table 1B). In cases where summed-section weight was more than 50% different than the reported scale weight, it was decided the scale weight data was untrustworthy. These trees were excluded from the biomass analysis.

Seventeen of the forty trees were measured on a portable digital scale, in sections. This was done for trees smaller than 10’’ DBH, where it was not practical to transport such small diameter trees one at a time to the industrial scale.

Photos were used to categorized trees according to the amount of branches, or “branchiness”, for the purpose of determining if sapwood or biomass is influenced by braching form. A rating scale of 1-4 was used to evaluate branchiness, 1 being not very branchy, 4 being very branchy

Figure 1. Branchiness categorical examples:

Figure 1: Clockwise, Tree 22, branchiness category 1 ; Tree 26, branchiness category 2 ; Tree 34, branchiness category 3 ; Tree 2, branchiness category 4.

A.3 Determining Biomass of Stumps

Since it was not possible to measure stump weight, an estimate was calculated using measured stump height and diameter (on top of stump) along with the formula for a cylinder. Stump estimates were added to measured weights in order to compare data to models which included stump weights/volumes.

Stump volume (cubic inches) = π * (Stump Radius^2)* (Stump Height)
(where both stump height and stump radius were measured in inches)
Stump weight (pounds) = (Stump volume/1728)*60

1728 is the conversion from cubic inches to cubic feet. 60 is the average green weight in pounds of bark and wood per cubic foot of green ash, taken from Miles and Smith (2009).

Stump weight was then added to measured weight of the rest of the tree to provide a total aboveground biomass figure.

B. Biomass Model Comparisons

Measured weights were compared to predicted weights from Hahn (1984) and Jenkins et al. (2003). Mean differences and mean absolute differences between measured weights and those predicted by Hahn and Jenkins et al. formed the basis of comparison.

Field data was used to fit both models in a effort to improve upon their predictability. We also experimented with a dummy variable for branchiness (1 = not many branches, 0 = branchy). We examined the interaction between the branchiness variable and D^2H.

B.1 Hahn formula

Published in 1984, this model uses an added components approach. Components volumes for the main stem, or bole, divided into a saw log portion and upper stem, as well as components for top and limbs, bark and a 1-foot stump. Field measurements for tree height and diameter at breast height are used to compute cubic foot volume for each component using the formula $V=B0 + B1DBH^2H$. The bole volume calculations use merchantable height to a four-inch top. These component volumes are obtained via equations containing ash-specific species correction factors.

Hahn model components:

1.) gross volume of the bole with ash-specific coefficients:

$V = 1.5280 + 0.002021^x(DBH^2)^xH$
Standard error = 6.84 ft^3
$R^2 = .91$

2.) Stump volume with ash-specific stump coefficient = 0.008728^xDBH^2

3.) Species correction factor for bark differences with ash-specific coefficients:

$(91.834+0.325^{x}DBH)/100$

4.) Bole bark weight (lbs.) = (gross cubic foot volume + stump volume)^{x}(1.1646 – species correction factor)^{x}37

5.) Bole green weight of merchantable portion of tree, using ash-specific weight coefficient (tons) = bark + (gross cubic foot volume + stump volume)^{x}49)/2000

6.) Top weight, or section above merchantable portion of tree (tons) = 0.4545^{x}(bark + gross volume^{x}49)/2000

7.) Add bole weight to top weight for total biomass in green tons

The model assumes one cubic foot of green ash (green weight) material weighs 49 pounds. The model is applicable only for trees 5 inches DBH and greater, with bole measurements up to a 4-inch diameter top. For trees smaller than 5 inches DBH, the model uses another formula developed by Raile (1982).

The US Forest Service employs the Hahn model for estimating the biomass of its Forest Inventory and Analysis plots in the Lake States (Hansen, 2002).

B.2 Jenkins formula

Published in 2003, **t**he Jenkins model is diameter-based, using wood-specific gravity to determine weights. The model is not specific to green ash, but is general to "mixed hardwoods." Raile's 1982 stump biomass model was incorporated into the model.

Jenkins et al model, with coefficients for mixed hardwood (i.e. green ash):

$$B_m = \exp(-2.48 + 2.4835 \ln(dbh_{cm}))$$

B.3 Comparing Biomass Models

Mean differences between both models and field data were calculated. These mean differences were used to perform an equivalence test. Equivalence tests assess whether there is a practical difference in means. A threshold is chosen, in this case 30%*SD, or .30. Equivalence tests use Two One-Sided Tests (the package TOST in R). (Robinson 2016, Moore et al., 2009)

C. Sapwood

Sapwood and heartwood diameters were measured for sections of the main stem, as well as at the intersection of main branches to the main stem. On each wood sample, or cookie, measurements were taken at four points of the cross-section, then averaged, to yield an average sapwood radius. This average was then doubled, to give a sapwood diameter. Heartwood was measured at two points, giving an average diameter. Heartwood and sapwood/heartwood combined volumes were calculated using Smalian's formula:

0.0027274*(average large diameter^2+ average small diameter^2)*length of section. (diameter measured in inches)

In order to calculate sapwood volume, heartwood volume was subtracted from a combined sapwood/heartwood value. For main sections in which sapwood was not measured, a diameter estimate was used, with the nearest cookie as a reference, along with the length of the estimated section. Branch sapwood volume was calculated similarly, subtracting heartwood volume from combined heartwood/sapwood volume. However in lieu of Smalian's formula, a conical formula was used. This was due to the lack of diameter data for the ends of the branches. These volumes were then summed to yield an approximation of whole-tree sapwood volume.

Next, regression analyses were fit using dependent variables for Crown Volume and Crown Surface Area, Another dependent variable (D^2H) combines Height and DBH. Total tree sapwood volume serves as the response variable for all these regression analyses.

Crown dimensions were assessed using the following calculations:

Crown Volume = 0.5*(average crown width)^2/4* π * h

Crown surface area = $(\pi/6)(r/h^2)[(r^2 + 4h^2)^3/2 - r^3]$

Where:
r = average crown width / 2
h = vertical length of crown
(All units in feet)

IV. RESULTS

A. Biomass

Green weight biomass measurements ranged from 58.5 lbs. to 15560 lbs., with a mean of 3540, and a mean biomass per inch of 163.1 lbs (Table 1).

Table 1. Field data summary (all units in lbs.)

	Mean	Standard deviation	Minimum	Maximum
DBH	13.8	9.2	3	33
Height	42.2	19.6	18	88
Biomass	3540	4447.8	58.5	15560
Biomass per inch of diameter	163.1	146.2	15.3	471.5

Table 2 presents a report of measured data alongside values generated from models by Hahn and by Jenkins et al. Data from trees 4 and 15 were not included in the biomass analysis due to untrustworthy scale data. Tree 37 was found to be unsuitable due to multiple branching below breast height.

50% of the trees in the study had good form and low branchiness (1 on the branchiness scale), while the remaining trees had poor form and high branchiness (2-4 on the branchiness scale). The dummy variable was not significant in determining biomass volume.

Table 2. A summary of field measurements compared to both Hahn and Jenkins models. Leaves were not accounted for in any of the models.

Tree number	Diameter at Breast Height (inches)	Total Height (feet)	Measured Green Weight (lbs) plus stump estimates	Hahn Predicted Green Weight (lbs)	Jenkins Predicted Green Weight (lbs)	Branchiness rating	Dummy
1	20.7	61	5033	4616.6	5016.0	1	1
2	24.3	62	9400.6	6361.0	7469.6	4	0
3	22.4	62	7987.8	5446.4	6102.2	2	0
5	30.1	55	9702.4	8553.7	12710.6	4	0
6	21.3	50	5754.8	4059.4	5384.9	4	0
7	22.1	62	5216.7	5308.3	5901.2	3	0
8	19	52	4298.4	3390.3	4054.4	2	0
9	11.4	39	1355.2	1039.8	1140.2	3	0
10	11.8	40	1854.4	1127.3	1242.1	3	0
11	13	27	1806.5	972.6	1579.9	2	0
12	15.3	25	2468.8	1214.8	2367.7	2	0
13	13	41	2035.9	1365.9	1579.9	2	0
14	25.9	69	11727.4	7943.1	8751.3	3	0
16	19.1	49	2740.5	3244.5	4107.6	2	0
17	33	73	15560.9	13309.7	15972.6	4	0
18	8.3	48	503.5	718.6	518.4	1	1
19	6	36	295.3	365.4	231.6	1	1
20	5.4	26	274.1	271.4	178.3	1	1
21	3	18	58.5	56.6	41.4	1	1
22	5.7	19.5	153.1	251.9	203.9	1	1
23	7.8	27	388.5	435.5	444.3	1	1
24	8.5	29	645.2	516.8	550.0	1	1
25	3.7	19	107.6	94.3	69.7	1	1
26	26	63	7382.7	7346.2	8835.5	2	0
27	9.5	35	838.5	703.3	725.0	1	1
28	4.7	25	137	168.7	126.3	1	1
29	4	21	110.8	114.0	84.6	1	1
30	4.5	25	111	151.8	113.3	1	1
31	4.8	26	128.9	177.6	133.0	1	1
32	4.4	25	100.8	143.7	107.2	1	1
33	3.9	22	59.7	107.2	79.4	1	1
34	30.3	79	12639.1	12190.2	12921.3	3	0

35	26.9	88	11791.5	10757.5	9614.7	2	0
36	27	80	9771.2	9893.7	9703.7	2	0
38	6	32	283.2	341.1	231.6	1	1
39	9.6	30	805.5	638.2	744.1	1	1
40	8.8	33	701.1	596.4	599.5	2	0
41	6.5	33	303.2	384.9	282.5	1	1

A summary of the mean differences as well as mean absolute differences between field data and Jenkins et al., and Hahn can be found in Table 3. Hahn had a lower mean difference, while Jenkins et al. had a lower mean absolute difference.

Table 3: Summary statistics of differences between field data and Jenkins and Hahn predicted values.

	Mean Absolute difference (lbs.)	Mean difference (lbs.)	Mean Absolute difference (%)	Mean difference (%)
Jenkins	508.2	137.5	16.9%	5.1%
Hahn	614.6	535.5	24.4%	1.0%

Equivalence Tests

Tables 4 and 5 show the results of fitting the Jenkins et al. (2003) and Hanh (1984) biomass models to the measured weights. The Hahn Refit model seems to have the best fit to field data, resulting in the smallest mean difference between observed biomass and predicted biomass. Using the field data collected in this study and refitting the Hahn model produced an “equivalent” result in an equivalence test. The fit of the Jenkins et al. model to field data also improved when tree height data was included. In both cases where height was included as a variable, model fits were improved in terms of error and mean difference. Neither attempts to fit Jenkins et al. to field data resulted in equivalence.

Fitting Jenkins et al. model to measured data reduced the mean difference by 90%. Fitting data to Hahn’s model reduced the mean difference by 199.4%.

Hahn was slightly improved again when branchiness was added. With a branchiness coefficient of -827 lbs. In short, a “branchy” tree would have 827 lbs more than a “non-branchy” tree wih the same D^2H value.

Table 4. Biomass Model results (standard error in parentheses)

Model type	Model form	B_o	B_1	B_2	Residual Standard Error (lbs)	Adjusted R^2
Jenkins et al (2003) Refit	$B_m = \exp(Bo+B_1 * \log(DBH))$	1.8865 (.48)	2.2166 (.14)	No value	950.7	N/A
Jenkins et al Refit with Height	$B_m = \exp(Bo+B_1 * \log(DBH) + B_2 * \log(Height)$	0.4693 (.5427)	1.8394 (1.551)	0.6316 (4.098)	785.5	N/A
Hahn (1984) Refit	$B_m = B_0 + B_1 * D^2H$	3.156e+02 (1.756e+02	1.891e-01 (6.169e-03)	No Value	866.3	0.9621
Hahn Refit with D^2H and Branchiness	$Bm = B0 + B1*D^2H+B2*Branchiness$	927.05537 (302.48589)	0.17746 (0.00753)	-827.32389 (343.10235)	813.6	0.9665

Table 5. Biomass equivalence test results

Comparison to Field Observations	Mean difference (lbs)	SD of diff	Equivalence Test Result
Jenkins et al (2003)	121.4	972.8624	Not equivalent
Jenkins et al Refit	-50.39001	936.3893	Not equivalent
Jenkins et al Refit with Height	-25.64417	763.5946	Not equivalent
Hahn (1984)	530.3851	967.579	Not equivalent
Hahn Refit	0.0	854.5396	Equivalent
Hahn Refit with Branchiness	0.0	791.3333	Equivalent

The equivalence test takes into account both the mean difference and the standard deviation of the difference when determining equivalence. In this case, Jenkins et al. refit with height, the mean difference was large in absolute value, even though the standard deviation is smaller compared to Hahn refit (Table 5).

B. Sapwood

Sapwood volumes among individual trees ranged from 0.5 cubic feet to 54.1 cubic feet, with a mean of 16.22 (Table 6).

Table 6. Sapwood summary ($ft^{3)}$

Min	Median	Mean	Max
0.5	9.975	16.22	54.10

Table 7. A report of field measurements of sapwood volume and growth rings

Tree number	DBH	Sapwood Volume (ft^3)	Growth ring count of DBH sample
1	20.7	19.89	68
2	24.3	37.9	48
3	22.4	35.3	44
4	6.5	0.5	24
5	30.1	44.5	55
6	21.3	54.1	47
7	22.1	31	78
8	19	24.1	52
9	11.4	8.6	37
10	11.8	13.4	36
11	13	15.1	38
12	15.3	13.5	50
13	13	16.7	37
14	25.9	52.4	70
15	17.2	30.4	33
16	19.1	11.4	57
17	33	40.8	140
18	8.3	3.4	30
19	6	0.8	32
20	5.4	3.1	15
21	3	0.8	15
22	5.7	0.9	18
23	7.8	3.7	37
24	8.5	5	31
25	3.7	0.64	17
26	26	25.3	58
27	9.5	4.35	39
28	4.7	1.51	14
29	4	0.96	15
30	4.5	1.34	13
31	4.8	1.55	14
32	4.4	1.23	16
33	3.9	0.82	14
34	30.3	67.6	137
35	26.9	52.34	99
36	27	28.1	122
38	6	4.73	31
39	9.6	7.18	35
40	8.8	13.1	32
41	6.5	11.35	33

*tree 37 excluded due to multiple stems below dbh.

Using R, a regression analysis was performed for sapwood volume on DBH (Table 8). This equation gives an approximation of average cubic foot volume of sapwood aboveground for a given DBH. It does not account for root sapwood.

Table 8. Total sapwood volume~DBH^2 (t statistics in parentheses)

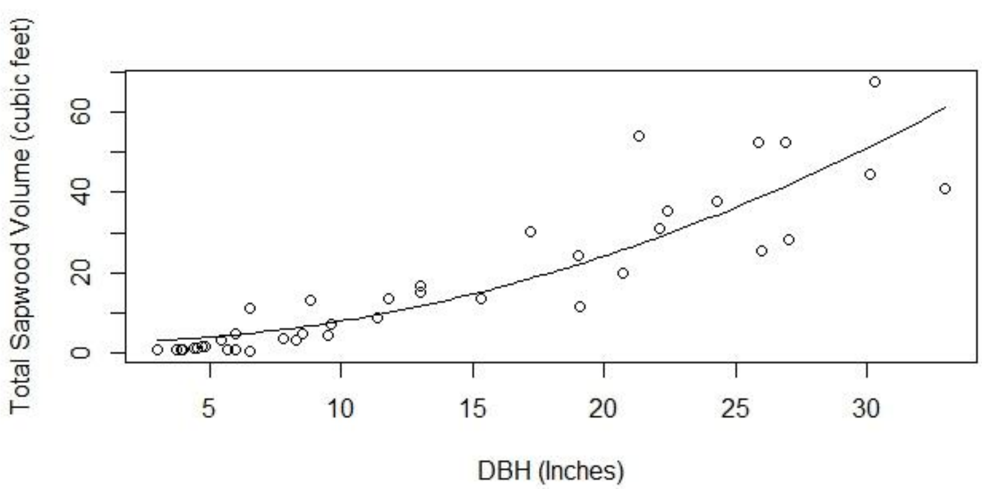
B_0	B_1	Adjusted R^2	Residual Standard Error ($ft^{3)}$
2.628230 (1.461)	0.053815 (12.14)	0.7896	8.457

Total Sapwood Volume = 2.62823 + (0.053815*DBH^2)

The above equation implies sapwood volume increases by .053815 cubic feet for each square inch change in DBH^2. Cross-sectional area equals .005454*DBH^2 (DBH in inches), therefore a cubic foot increase of 053815/.005454, or 9.867 in sapwood volume would result in each square foot increase in cross-sectional area.

Sapwood distribution by DBH shows a non-linear relationship, with greater variability as diameter increases. The non-linear sapwood volume model is show in figure 1 as a curve. Volume increases at an increasing rate with DBH.

Figure 1. Sapwood volume versus DBH



In table 9, a series of regression models shows the results of several different variable combinations used in predicting sapwood volume. Among these, crown surface area (S3), by itself, seems to be the best predictor of sapwood volume, with the highest adjusted R-squared and the lowest residual standard error. This is in accord with previous research on sapwood and its relationship with crown size (Maguire and Hann 1989).

Formula for estimating sapwood using the preferred model (S3) for crown surface area:

Total Sapwood Volume = -2.5125246 + (0.0089602*Crown Surface Area)

Table 9. Sapwood models - results and comparisons (t-statistics in parentheses)

Model	Sapwood Volume (dependent variable)	B_0	B_1	B_2	Adjusted R-squared	Residual Standard Error (ft^3)
S1	~D^2H	5.447e+00 (3)	7.099e-04 (10.95)	No value	0.75	9.16
S2	~Crown Volume	3.144e+00 (1.8)	9.613e-04 (12.4)	No value	0.78	8.27
S3	~Crown Surface Area	-2.5125246 (-1.41)	0.0089602 (14.63)	No Value	0.8453	7.251
S4	~D^2H + Crown Volume	3.44 (2)	0.0002 (1.44)	0.0006 (3.3)	0.80	8.15
S5	~ D^2H + Crown Surface Area	-1.875e+00 (-0.88)	8.062e-03 (4.74)	8.079e-05 (0.56)	0.8425	7.36
S6	~D^2H + Branchiness	-3.948e+00 (2.577e+00)	4.996e-04 (7.103e-05)	6.965e+00 (1.566e+00)	0.8349	7.492

It was curious that DBH^2 by itself seemed to be predicting sapwood volume better than D^2H, since it would make sense that adding height would certainely benefit. This led to investigating the impact of branchiness on that relationship. We examined the lowest category (Branchiness =1) versus other categories (Branchiness = 2,3 or 4). To investigate whether the branchiness categorical variable had an impact on the relationship between sapwood volume and tree dimensional characteristics. Model S1 versus model S6, it is apparent that branchiness significantly impacts the relationship between D^2H and sapwood.

V. DISCUSSION

A. Biomass

Nowak's (1994) finding that allometric models overestimated woody biomass is validated with this study, as both Hahn and Jenkins et al. models had positive differences from field measurements. Nowak et al. (2003) found models based on forest-grown trees overestimated by 25% urban woody biomass on trees that were intensively pruned.

Our field measurements were lower than what Jenkins et al. or Hahn predicted, although not by as much as what Nowak et al. reported. This difference in results might be attributed to the fact that Nowak's study did not focus on one species, was based in a different locale, and had only 3 ash trees measured in his study.

Branchiness does indeed affect biomass volume, more so than the height variable.

A1. Equivalency

Neither of the two published models satisfied the equivalence test criterion, therefore it appears that for this population of urban trees, new fitted models are a significant improvement over the original published models.

A2. Fit

Hahn appears to be the most robust model, when it is fitted to measured data. Adding a height variable to the Jenkins et al. model improves its predictive ability, lowering the residual standard error, while making it competitive with the Hahn refit model. Jenkins et al. mean differences were lowered, from 121 to -25. This is not surprising, as it is typical that model predictive ability is improved when tree height is used in combination with diameter. This reflects the allometric relationship between tree form and volume (Picard et al. 2012).

The mean difference for the Hahn model was improved, from 530 to essentially zero difference from predicted values using fitted data. Goerndt et al. (2014) conducted a similar study using forest-grown hardwood species in Missouri. In that study, fitting measured data with added height as a variable, they were also able to improve upon the Jenkins et al. model form. Data which captures the local variations in tree growth and form appear to be quite useful in localizing published models.

B. **Sapwood**

Model S3 provides the best predictive capability for sapwood volume, beyond that which the DBH variable alone provides. Crown surface area plays an important role in determining sapwood volume, more so than diameter of the stem.

It makes intuitive sense that more leaf area translates to a higher volume of sapwood. The pipe-model theory tested the relationship between the amount of foliage and the volume of xylem material needed to support it (Shinozaki et al. 1964). Research has suggested seasonal downward flow of materials into the root system (Tattar and Tattar, 1999), white ash being part of the study. Downward flow occurred "evenly split" to upward flow during spring and summer, with an increase as soil temperatures decreases in the fall, and yet another increase after leaf senescence. Downward flow also increased at times when soil moisture was low. Research has also shown a higher cross-sectional area of sapwood in the roots versus the rest of the tree (Gould and Harrington, 2008).

C. Management Implications

C.1 Biomass

When the added cost of measuring tree height is prohibitive, the improved Jenkins et al. refit model would serve the purpose of estimating tree biomass. If program constraints allow for measuring tree height, the improved Hahn refit model would more accurately generate biomass estimates.

C.2 Sapwood

A chemical compound known commercially as "Tree-age' is commonly applied for treatment of emerald ash borer infestations. Since EAB only enters the aboveground portion of a tree and research has shown higher amounts of xylem tissue in roots, it follows that much of the applied dosage might enter the roots and not serve the purpose of controlling EAB. Whether the chemical enters the stem or the roots depends on factors such as weather, time of day, time of season and air/soil moisture conditions. These factors should be taken into account before attempting to modify dosages using this model. It is helpful to keep in mind that sapwood volume has more to do with crown size than DBH. If possible, measurements for crown dimensions would improve chemical treatment dosage accuracy.

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LITERATURE CITED AND REFERENCES

Gould, P., Harrington, C. 2008. Extending sapwood – leaf area relationships from stems to roots in Coast Douglas-fir. Annals of Forest Science 65 (2008) 802.

Goerndt, M. E.; Larsen, D. R.; Keating, C. D. 2014. Evaluation of total aboveground biomass and total merchantable biomass in Missouri. In: Groninger, John W.; Holzmueller, Eric J.; Nielsen, Clayton K.; Dey, Daniel C., eds. Proceedings, 19th Central Hardwood Forest Conference; 2014 March 10-12; Carbondale, IL. General Technical Report NRS-P-142. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 234-250.

Hahn, J.T. 1984. Tree volume and biomass equations for the lake states. Research Paper NC-250. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station.

Hansen, M. 2002. Volume and biomass estimation in FIA: national consistency vs. regional accuracy. In: McRoberts, Ronald E.; Reams, Gregory A.; Van Deusen, Paul C.; Moser, John W., eds. Proceedings of the Third Annual Forest Inventory and Analysis Symposium; Gen. Tech. Rep. NC-230. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 109-120.

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National-scale biomass estimators for United States tree species. Forest Science, Vol. 49, No. 1: 12-35.

Maguire, D.A., Batista, j. 1996. Sapwood taper models and implied sapwood volume and foliage profiles for coastal Douglas-fir. Canadian Journal of Forest Research 26: 849-863.

Maguire, D.A. and Hann, D.W. 1986. Equations for predicting sapwood area at crown base in Southwestern Oregon Douglas-fir. Canadian Journal of Forest Research 17: 236-241.

Maguire, D.A. and Hann, D.W. 1989. The relationship between gross crown dimensions and sapwood area crown base in Douglas-fir. Canadian Journal of Forest Research 19: 557-565.

Miles, P. D., Smith, W.B. 2009. Specific gravity and other properties of wood and bark for 156 tree species found in North America. Res. Note NRS-38. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Moore, D. S., McCabe, G.P. and Craig, B.A. 2009. Introduction to the practice of statistics. New York: W.H. Freeman.

Nowak, D.J., Stevens, J.C., Sisinni, S., Luley, C.S. 2003. Effects of urban tree management and species selection on atmospheric carbon dioxide. Journal of Arboriculture 28 (3): 113-122.

Nowak, D.J. 1994. Atmospheric carbon dioxide reduction by Chicago’s urban forest, pp 83–94. In McPherson, E. G., D.J. Nowak, and R.A. Rowntree (Eds.). Chicago’s Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. USDA Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

Picard, N., Saint-Andre, L., Henry, M. 2012. Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier, 215 pp.

Robinson, A. (2016). Equivalence: provides tests and graphics for assessing tests of equivalence. R package version 0.7.2. https://CRAN.R-project.org/package=equivalence.

Sellin, A. 1993. Sapwood-heartwood proportion related to tree diameter, age, and growth rate in Picea abies. Canadian Journal of Forest Research, volume 24: 1022-1028.

Shinozaki, K., K. Yoda, K. Hozumi ard T. Kira. 1964. A quantitative analysis of plant form-the pipe model theory. I. Basic analyses. Japanese Journal of Ecology 14, 97-105.

Tattar, T.A. and Tattar, S.J. 1999. Evidence for the downward movement of materials injected into trees. Journal of Arboriculture, Vol. 25:325-332.

Vanderschaaf, C.L., Jaboson, K. 2011. Estimated Impacts of Emerald Ash Borer (EAB) on Ash Timber Supply in Minnesota. Minnesota Department of Natural Resources.

Whittaker, R.H.; Woodwell, G.M. 1968. Dimension and Production Relations of Trees and Shrubs in the Brookhaven Forest, New York. The Journal of Ecology, Vol. 56, No. 1: 1-25.